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LAND USE IN LCA

Climatic impact of land use in LCA—carbon transfers between vegetation/soil and air

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Abstract

Background, aim, and scope Human use of land areas leads to impacts on nature in several ways. Within the framework of the UNEP/SETAC Life Cycle Initiative, it was stated that life cycle assessment (LCA) of land use should assess at least the impact on biodiversity, the impact on biotic production, and the impact on the regulating functions of the natural environment. This study focuses on the climatic impact of land use as determined by the CO_2 transfers between vegetation/soil and the atmosphere in the course of terrestrial release and re-storage of carbon.

Materials and methods Compared with the potential natural vegetation as a baseline, areas getting transformed by man (land transformations) as well as areas forced to maintain their current non-natural state (land occupations) may store reduced amounts of carbon in soil and vegetation, whereby the mobilized carbon is essentially transferred to the atmosphere in form of CO_2, contributing to global warming. The size of this climatic impact is determined by the amount of carbon transferred per hectare, as well as by the duration of the carbon's stay in air. Generally, we consider this duration as limited by spontaneous reversal of vegetation and soil toward a quasi-natural form as soon as human land use ends. Taking the mean stay in air of 1 ton carbon from fossil fuel combustion as a basis of comparison, 1 ton carbon released by, e.g., a forest-to-cropland transformation can be adequately weighted by considering the timing of carbon backflow from air to the spontaneously regrowing forest.

Results Carbon transfers to the air per hectare, as well as imputable durations of carbon stay in air, are determined for the most important types of land transformation and land occupation, for locations in any of the terrestrial biomes of tropical forest, temperate forest, boreal forest, tropical grassland, and temperate grassland. The carbon quantities are expressed as "fossil-combustion-equivalent" tons of carbon so that they can be summed up with carbon amounts from fossil fuel combustion into the usual LCA indicator for global warming potential.

Discussion The results confirm that on a per hectare basis, transforming forests into cropland has a more serious climatic effect than continuing to occupy such land as cropland for one additional year. But on a global basis, maintaining current cropland areas for one additional year is a serious driver of global warming due to the huge area of croplands in zones where forest would be the natural vegetation. Furthermore, forest-to-cropland transformations cause carbon transfers to air per hectare of roughly similar size in tropical, temperate, or boreal zones, but due to slow forest restoration, transformation of boreal forests has a stronger influence on global warming.

Conclusions and recommendations The results of this study facilitate a worldwide impact assessment of land use with respect to global warming. Together with the two separate studies covering the impacts of land use on biodiversity and on biotic production, a tool will be available for a reasonably complete LCA of land use at global level. However, the data quality needs further improvement.

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1 Background, aim, and scope

Land use leads to many types of impacts on nature. Milà i Canals et al. (2007) propose to include in life cycle assessment (LCA) of land use at least three important impacts: the impact on biodiversity, the impact on biotic production, and the impact on the regulating functions of the natural environment. This study concentrates on the last of these pathways dealing with release and storage of carbon in vegetation/soil and their climatic impact. The conceptual framework of Milà i Canals et al. (2007) is respected; we recommend the reader first to familiarize himself with this framework.

Land use on a given area influences the climate system in various ways, in particular:

- CO_2 flows between land and atmosphere may be modified due to a change of the area's carbon storage in vegetation and soil, influencing the absorption of solar radiation by the atmosphere (radiative forcing).
- The flow of greenhouse gases other than CO_2 may be modified.
- The albedo of the area may be modified, influencing the reflection of solar radiation at earth's surface.
- The evapotranspiration of the area may be modified, influencing precipitation and the reflection of solar radiation by clouds.

Due to the outstanding importance of CO_2 emissions on radiative forcing (IPCC 2007:136) and due to the substantial share of land use change (=land transformation in LCA language) as a source of CO_2 emission (IPCC 2007, Table 7.1), the main focus in this study is on the influence of land use on the transfers of CO_2 between atmosphere and land, the latter including soil and its vegetation. We aim at quantifying this influence for each of the earth's main biogeographical zones and for each of the main types of human land use (urban land, forest, pasture, and cropland). However, we concentrate here on the CO_2 flows caused by land use in the narrow sense inducing quality change in soil and vegetation, and we do not treat CO_2 flows caused by applying machinery or auxiliary materials (like motor fuels or fertilizers), nor do we determine here the CO_2 merits of products grown in the particular case of cropland use: Our study is not a product LCA for biofuels.

Nevertheless, two elements of our study offer interesting comparisons with biofuel studies (Zah et al. 2007; Searchinger et al. 2008; Fargione et al. 2008; Reijnders and Huijbregts 2008). First, we determine the CO_2 impact during the time of land occupation primarily by subtracting the carbon content in vegetation and soil of currently occupied land from the carbon content of land covered with natural vegetation even if this natural vegetation has been absent locally for a long time. In contrast, biofuel studies typically do not take into account the potential natural state of land; this means that the current land occupation may show a zero CO_2 impact if the management practice happens to be carbon-neutral. To avoid this undesirable outcome, the current land occupation is charged by the indirect effect of supposed land conversions at other locations (Searchinger et al. 2008) or by a carbon debt due to a recent land conversion (Fargione et al. 2008), both requiring delicate assumptions. Second, our study respects the fact that the climatic impact of CO_2 in the air depends not only on the CO_2 quantity but also on its duration of stay in air. We show that the time to fill up a carbon sink created by land transformation varies largely in dependence of the geographical zone and the type of land use. In contrast, typical biofuel studies do not cover this time aspect.

2 Materials and methods

In LCA, the widely used indicator for CO_2 emissions from fossil fuel combustion and similar technical processes is expressed in (metric) ton or in megagram (Mg) of CO_2. To facilitate the interpretation of LCA results, it is desirable to apply this same indicator also for CO_2 emissions from land use origin. However, the climatic effect of CO_2 transferred to the air depends not only on the tonnage transferred but also on the average time the respective CO_2 quantity stays in the air. It is thus necessary to compare the behavior in time of the two CO_2 flows: If the imputable average stay in air of CO_2 from land use origin is shorter than the average stay in air of CO_2 from fossil combustion, the CO_2 emission quantities from land use are to be weighted by a factor <1 to adjust for their smaller warming effect per ton. These CO_2 flows are analyzed hereafter, determining in Sections 2.1 and 2.2 the imputable stay times in air for the various origins of CO_2 and describing in Section 2.3 the impact assessment model, with the determination of the carbon quantities per hectare for land transformation and land occupation and their time weighting. In Section 2.4, the sources of empirical data are presented, and the extracted data are processed in such way that the link to the numerical results in Section 3 is transparent.

2.1 The general carbon cycle model

According to the Bern carbon cycle model, a pulse of CO_2 emitted to the air will degressively disappear from the atmosphere (Fig. 1).

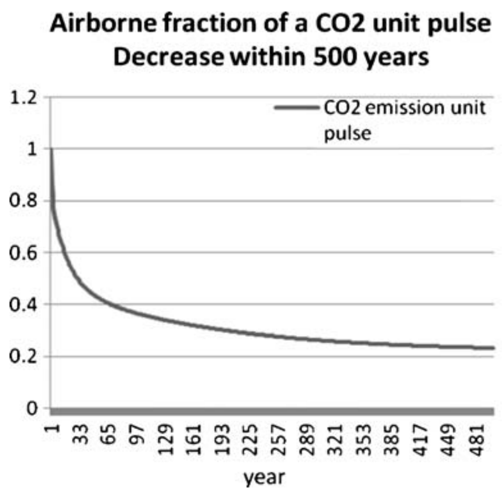

Fig. 1 Fraction of a CO_2 emission pulse which is still in the air after N years according to the Bern carbon cycle model with conditions valid at present: $y = 0.217 + 0.259 \times \mathrm{EXP}(-t/172.9) + 0.338 \times \mathrm{EXP}(-t/18.51) + 0.186 \times \mathrm{EXP}(-t/1.186)$ (Source: IPCC AR4 WG1, Tab 2.14)

Figure 1 shows this development: An initial CO_2 quantity of 1 unit is expected to decrease to 0.36 units after 100 years and to 0.23 units after 500 years. A residual of roughly 0.22 units is expected to remain in the atmosphere "for many millennia" (IPCC 2007:824), or even forever, if the underlying equation is assumed to be applicable for $t=\infty$. However, the equation is valid only for the conditions prevailing around year 2000.

As the global warming effect of a CO_2 quantity depends on its average stay in air, we want to find out from Fig. 1 the average time a CO_2 molecule stays in air. A meaningful average can be calculated only if the curve is cut off after a finite number of years, which means that the climatic influence of CO_2 after this cutoff point is considered to be negligible. A cutoff at year 100 would result in a mean CO_2 stay in air of 47.5 years, while a cutoff at year 500 gives a mean stay in air of 157 years. The choice of this cutoff point should be such that comparisons with CO_2 originating from land use are not heavily distorted; it can be shown that a cutoff at year 100 would be too short, unduly favoring carbon from fossil combustion, so that we prefer a cutoff at 500 years.

According to IPCC (2000:5), the CO_2 leaving the air is transferred to the oceans and to the terrestrial part of the globe. We suggest to call "dissipative" this CO_2 backflow to oceanic/terrestrial compartments because it is broadly distributed over the globe's whole surface. Furthermore, it is important to state here that the CO_2 pulse model determines the decrease of the airborne fraction of CO_2 under the assumption of "no concomitant land use change." This means that the decrease curve in Fig. 1 corresponds to the carbon backflow from the air to the oceanic sink and to the "residual terrestrial sink" (IPCC 2000:5), the latter determined by the global state of land use as it was before the time of emission of this CO_2 unit pulse (phone conversation with Prof. Fortunat Joos, University of Berne, on June 2nd, 2008).

CO_2 saturation of oceanic top layers is a particular problem. For the time being, we assume that the environmental damage of further carbon storage in oceans or in terrestrial vegetation/soil is nonsignificant. This assumption might change in the future on the basis of additional knowledge.

2.2 Atmospheric CO_2 originating from land use

The concept of land use impact assessment, as described in Milà i Canals et al. (2007), implies that a land transformation, on a given plot of land, is assessed in conjunction with its future relaxation: This means that the CO_2 released from, e.g., a deforestation is assumed to stay in the air until spontaneous regeneration by the forces of nature (relaxation) of the forest could have happened, inducing a CO_2 backflow "focused" on the area used. In the absence of any subsequent land occupation, relaxation toward the potential natural vegetation (PNV) starts immediately after the initial land transformation. But if a series of land occupations (e.g., planting of agricultural crops on a former forest area) follows after the land transformation, the relaxation is postponed by the number of years, N, of these land occupations. However, the corresponding prolongation by N years of the CO_2 stay in the air is an impact that is obviously attributable to the N years of land occupations and not to the initial land transformation. Hence, the damaging impact of a land transformation itself does not increase if a sequence of land occupations follows (from hereon, we express carbon stocks and flows in ton of carbon, t C, or megagram, Mg C, equivalent to 3.67 ton of CO_2).

This concept may be explained by the case of a temperate forest assumed to contain 100 t C per hectare in vegetation and 140 t C per hectare in soil, which is burnt down in year 0 and then starts to regenerate spontaneously to new forest, arriving at the same carbon quantities stored after 70 years of forest growth. Assuming that in short time the fire leads to a transfer to the air of 100% carbon ex vegetation and 25% of carbon ex soil, the atmosphere receives an increment of 135 t C per hectare. Then, reforestation causes a gradual retransfer of carbon back to the burnt area until all of the additional carbon in air has disappeard within 70 years. The average time to stay in air of the carbon is lower than 70 years: In fact, only a tiny part of the 135 t C per hectare stays in the air during the full period of 70 years, while the first backflow of carbon takes place when the growth of trees starts. As the exact carbon flows in time are not well known, we take the simplified assumption that the mean stay time in air of carbon is half of the relaxation time, or 70/2 years in our case.

If we compare now this carbon transfer to the air caused by land use with the carbon transfer according to Fig. 1, we

notice that average carbon stay in air originating from land use is substantially different from the 157 years of stay according to the general carbon cycle model. In consequence, 1 ton of carbon from any case of land use may cause a different global warming effect than 1 ton of carbon from fossil combustion. It is hence justified to weight a carbon quantity originating from land use with a “duration factor (df)” before it is added to carbon quantities originating from fossil combustion and comparable technical processes. This duration factor is the ratio between the average carbon stay in air due to the land use and 157 years. On the basis of empirical data, this duration factor can be determined for the various types of land use in the various climate zones of the globe. It may be expected that regeneration of wet tropical forests is fast (df clearly lower than 1), whereas regrowth of boreal forests is slow. Nevertheless, we do not propose a df higher than 1 in the second case because carbon from destruction of vegetation with slow regeneration can always leave the atmosphere through the “dissipative” outflow path towards the oceans and the continents.

It is important to eliminate here two types of possible misunderstandings. First, the carbon backflow to the area of a regrowing forest does not consist of the same individual molecules as the carbon flow to the air during the previous forest destruction. The plants do not distinguish between molecules of fossil origin and molecules of land use origin so that a carbon sink on a cleared land area may well be filled up with carbon from any origin. If we say that the carbon stay in air from a destroyed wet tropical forest is 35 years, this refers to carbon quantities, not to individual molecules. We therefore use the term “imputable” stay time. Second, a quantity of carbon leaving the air will in reality be partitioned among the various parallel outflow paths, be it to the broad oceanic/terrestrial surface (“dissipative” carbon backflow) or to the demarcated areas of specific land use (“focused” carbon backflow). It is for the sake of simplicity that we determine the average time of carbon stay in air under the assumption that carbon quantities mobilized by land use flow essentially back to the place of their origin if this “focused carbon backflow” is faster than the 157 years of the “dissipative” carbon backflow.

The need of taking into account the duration of the carbon stay in air before adding carbon quantities of different origin has already been mentioned by Moura-Costa and other authors (see IPCC 2000, Section 2.3.6.3).

2.3 The life cycle impact assessment model of carbon transfers due to land use

We propose to model in LCA the climatic impact of land use as follows:

- The impact indicator is expressed in ton of CO_2 and represents the CO_2 mobilized from vegetation and soil due to land use activities in the narrow sense. This means that the impact indicator traditionally used in LCA practice for fossil and industrial global warming potential (GWP) emissions is also applicable for climatic impacts from land use. However, we calculate here in ton of carbon, t C, equivalent to 3.67 ton of CO_2. In a first step, we concentrate on carbon flows in the form of CO_2 and exclude flows of other GWP gases.
- The climatic impact of a carbon unit in the atmosphere depends on the duration of its mean stay in air. Carbon from fossil combustion and similar industrial processes has an average time to stay in air of 157 years if flows after year 500 are excluded. If a mean carbon stay in air of <157 years is imputable to a given type of land use, a weighting of the mobilized carbon quantity by a duration factor is necessary to ensure an adequate summation with carbon quantities from fossil origin. The duration factor equals the imputable carbon stay time in air, divided by 157 years, but it cannot exceed the value of 1 (carbon from land use can be less damaging, but not worse than carbon from fossil combustion).
- For a land transformation, the imputable mean stay of carbon in air is 50% of the relaxation time (time needed by the forces of nature to reverse the transformation). This means that relaxation is assumed to progress in proportion to time for the sake of simplicity. For a land occupation, the imputable mean stay of carbon in air is equal to the occupation time because the carbon transmitted to the air by a previous land transformation extends its stay by the length of the occupation.
- The reference for determining carbon flows from land use is the carbon content of the specific PNV that is associated to each of the geographical locations of the globe. Approximative carbon stock quantities per hectare in vegetation and soil are available from field studies for the main types of PNV. Carbon quantities per hectare transmitted to or transmitted from air, due to the particular land use activity, can be derived from these stock data. For main types of land transformation, information on the transmitted percentage of carbon stock may be found in the literature. For land occupation, the carbon quantity in air is simply the difference of the carbon stock (in vegetation and soil) of the PNV and the actual carbon stock during the period of occupation. If the particular land occupation lasts 1 year, the stay in air of this carbon difference quantity is increased by 1 year, and the future relaxation is postponed by this 1 year.
- We start from the assumption that the land management of the occupied area is carbon-neutral so that observed changes of carbon stocks during the time of occupation are expected to be aftereffects of previous transformations, thus being a part of the transformation impact.

But if the occupation management itself is substantially non-carbon-neutral, our figures for occupation impact require a correction. The simple form of correction would be to convert the decreasing or increasing carbon stock during the period of occupation into a constant average carbon stock, thereby increasing or decreasing the difference to the PNV reference mentioned above. However, bearing in mind that the impact of carbon stock change during occupation does not stop at the end of this occupation, the more accurate form of correction would be to treat as an additional land transformation the net carbon change attributable to the occupation management method.

2.4 Empirical data on carbon storage and carbon flows

To determine the climatic impact of land use according to the precedent sections, data are required on the quantity of carbon per hectare transferred from vegetation/soil to the air, as well as on the imputable mean time to stay in air of this carbon. This data set should be available for all climatic zones of the globe and within each climatic zone for all types of land transformations and land occupations. To remain within reasonable limits of data requirements, the climatic zones are aggregated here into the six biomes most suffering from human land use: tropical forests wet/dry, temperate forests, boreal forests, tropical grasslands, and temperate grasslands. Furthermore, only those types of land transformations are considered which cause a substantial change of carbon storage in vegetation/soil.

2.4.1 Data on change of carbon storage due to land use

Table 1 presents data on mean carbon storage in vegetation and in the upper 1 m of soil for the gobal biomes (IPCC 2001, Chapter 3.2.2). A comparison of the data from the three different sources gives an impression of the limited accuracy. This impression of very coarse estimates is reinforced by comparison with a fourth available list of carbon stock data (Searchinger et al. 2008, Appendix D). We decide to work here with the German Advisory Council on Global Change (WBGU) carbon stock data because WBGU gives data for worldwide carbon flows caused by land use as well as information on the time dependence of these flows; we expect a better data consistency if the used data are collected and checked by one and the same research team. Furthermore, we consider it as an appreciation of quality that the WBGU findings were included into the IPCC publication. However, we had to correct WBGU figures for the case of temperate forests where an obvious calculating error for Australian temperate forests distorts the result (WBGU 1998, Anhang Tabelle 2). Furthermore, we decided to distinguish between the carbon storage of dry tropical forests and of wet tropical forests. In fact, this distinction was made in the original WBGU report: Wet tropical forests are estimated to contain 186 t C per hectare in plants and 180 t C per hectare in soil, while dry tropical forests contain only 50 t C per hectare in plants and 66 t C per hectare in soil (WBGU 1998:24; see Table 1).

When using the data of Table 1 for calculating the climatic impact of land use, it is necessary to allocate to the proper biome the place of the given land use. Global maps are available for this allocation task (IPCC 2007, Fig 2.15; WildWorld 2009). The maps generally do not show cropland (which does not represent a natural vegetation) and wetlands (which are usually parts of forest or grassland biomes).

The data we need for our calculations are not the carbon stocks in vegetation/soil as shown in Table 1 but rather the changes of stock as a consequence of land transformations: If forest is transformed to meadow, cropland, or building land, how much carbon will be transferred from vegetation/soil to the air? On the basis of available information (WBGU 1998, Chapter 6; Searchinger et al. 2008,

Table 1 Estimates of terrestrial carbon stocks (globally aggregated values by biome in megagram or ton of carbon) originating from WBGU, MRS, and IGBP (source: IPCC AR3 WG1, Table 3.2)

Biome	WBGU plants (Mg C/ha)	WBGU soil (1mMg C/ha)	MRS plants (Mg C/ha)	IGBP soil (1mMg C/ha)
Tropical forests	**120**	**123**	194	122
Temperate forests	57 corrected to **100**	96 corrected to **140**	134	147
Boreal forests	**64**	**344**	42	247
Tropical savannas and grasslands	**29**	**117**	29	90
Temperate grass and shrublands	**7**	**236**	13	99
Deserts and semi-deserts	**2**	**42**	4	57
Tundra	**6**	**127**	4	206
Croplands	**2**	**80**	3	122
Wetlands	**43**	**643**	–	–

The calculations in our study will be based on WBGU, except for temperate forests where we corrected an error (bold figures)

Appendix D), we answer these questions with the following simplifying assumptions:

- Forest-to-cropland transformations are transferring to the air 100% of carbon in vegetation and 25% of carbon in soil (top 1 m).
- Forest-to-pastureland transformations are transferring to the air 100% of carbon in vegetation and 0% of carbon in soil (carbon in soil remains reasonably protected by the permanent vegetation cover of grass so that mobilization of soil carbon is limited to small quantities).
- Forest-to-artificialland transformations are transferring to the air 100% of carbon in vegetation and 25% of carbon in soil (vegetation cover is generally disturbed by earth moving equipment so that soil loses its protection, similarly to the case of cropland).
- Grassland-to-cropland transformations are transferring to the air 25% of carbon in soil (permanent vegetation cover disturbed). The same applies to grassland-to-artificial land transformations. The change in vegetation carbon is negligible; however, according to Table 1, tropical grasslands contain a substantial amount of carbon in vegetation which we assume to be transferred to air in the case of these transformations.
- For the time being, the available information does not permit to fix more differentiated general rules for carbon stock transfers; this justifies it even more to assess the climatic impact only for the most important land transformations and to abstain from dealing with more differentiated types of transformation.

Going back to Table 1, it is evident that the carbon transfer of a forest-to-cropland transformation cannot be calculated by subtracting row "croplands" from the row of the transformed forest type because existing cropland is spread over the climatic zones of temperate forests, tropical forests, temperate grassland, and tropical grassland (see map Fig 2.15 in IPCC 2007, Chapter 2). The row 'croplands' therefore contains mean values that have no significance for a particular biome.

2.4.2 Data on relaxation times and on imputable mean CO_2 stay in air

To calculate the imputable mean duration of the carbon stay in air for the various types of land transformation, we want to know the number of years until practically all of the carbon is retransmitted to fill up the carbon sink on the transformed area. This is the time needed to accomplish relaxation on this plot. The duration of the relaxation period can be expected to be fast in a region of warm and moist climate and slow in regions of cold or dry climate. The data sources for determining the number of years for relaxation are incomplete and of limited consistency so that the resulting relaxation times are only a coarse estimate. The following data sources have been used:

- Chapter 6 of WBGU (1998) contains information on mean annual carbon storage rates in vegetation and in soil (WBGU 1998:55). But in IPCC (2000, Chapter 1.4.1), these rates are considered to "probably represent maximum rates achieved under intensive management that includes the use of fertilizers." For spontaneous natural relaxation, we therefore take for our calculations only 50% of the rates of WBGU (1998:55).
- Chapters 3 and 4 of IPCC (2000) contain further information on rates of carbon storage in vegetation and in soil per hectare for some types of land transformation.

The relaxation times obtained on the basis of these data sources are contained in Table 2. The calculation procedure is explained below for the upper three rows of Table 2: In the tropical forest biome, a forest-to-cropland transformation leads to a carbon transfer of 100% × 120 t C per hectare from vegetation to air and of 25% × 123 t C per hectare from soil to air, totalling 150.75 t C per hectare. According to WBGU (1998:55), the mean annual carbon backflow to vegetation/soil during the regrowth of tropical forests is 4.9 t C per hectare year, and we estimate that a purely natural regrowth would generate only 50% of this boosted backflow. The result is thus a relaxation time of 150.75/2.45=62 years. The duration of the imputable mean carbon stay in air is half of these 62 years, or 31 years, because the mean carbon stay in air is approximately the average between zero years and the number of years required for complete relaxation. A forest-to-pastureland transformation leads to a carbon transfer of 100% × 120 t C per hectare from vegetation to air, while carbon stock in soil is assumed to be roughly unchanged if there is no overgrazing. According to WBGU (1998:55), the mean annual carbon backflow to vegetation alone, during the regrowth of tropical forests, is 3.7 t C per hectare year. This results in a relaxation time of 120/1.85=65 years, the imputable mean stay of carbon in air being half of it.

A forest-to-artificial land transformation is assumed to lead also to a carbon transfer to air of 150.75 t C per hectare because the vegetation is removed and the soil is mechanically disturbed like in the case of cropland preparation. But in contrast to cropland, the surface of the area is often modified in such way that fertile soil is not immediately accessible to plant upcoming roots so that growth of any vegetation is retarded during a certain time. Experiences with spontaneous reforestation in the case of rockfall areas (Ceschi 2006), forefields of receding glaciers (Alean 2009), and areas covered with debris from volcanic eruptions (Frenzen 2009) support the very coarse assumption that spontaneous reforestation—if starting from artifi-

Table 2 Relaxation times and imputable mean carbon stay in air for main types of transformation in main biomes

Biome and type of preceding transformation (data source for carbon backflow rates in parentheses)	Carbon transfer (t C/ha)	Annual carbon backflow (t C/ha year)	Relaxation time (year)	Mean carbon stay in air (year)
Tropical forest: relaxation after forest-to-cropland transformation (WBGU 1998:55)	150.75	2.45	62	31
Tropical forest: relaxation after forest-to-pastureland transformation (WBGU 1998:55)	120	1.85	65	32.5
Tropical forest: relaxation after forest-to-artificial land transformation (WBGU 1998:55)	150.75	2.45	62	31+25
Temperate forest: relaxation starting after forest-to-cropland transformation (WBGU 1998:55)	135	1.83	74	37
Temperate forest: relaxation after forest-to-pastureland transformation (WBGU 1998:55)	100	1.35	74	37
Temperate forest: relaxation after forest-to-artificial land transformation (WBGU 1998:55)	135	1.83	74	37+50
Boreal forest: relaxation after forest-to-cropland transformation (WBGU 1998:55)	150	0.63	238	119
Boreal forest: relaxation after forest-to-pastureland transformation (WBGU 1998:55)	64	0.48	133	67
Boreal forest: relaxation after forest-to-artificial land transformation (WBGU 1998:55)	150	0.63	238	119+100
Trop. grassland: relaxation after grassland-to-cropland transformation (IPCC 2000, Table 4.4)	58	0.6	97	48
Trop. grassland: relaxation after grassland-to-artificial land transformation(IPCC 2000, Table 4.4)	58	0.6	97	48+25
Temp. grassland: relaxation after grassland-to-cropland transformation (IPCC 2000, Table 4.4)	66	0.6	110	55
Temp. grassland: relaxation after grassland-to-artificial land transformation (IPCC 2000, Table 4.4)	66	0.6	110	55+50

cial land with infertile topsoil—is retarded by 25 years in the tropical forest biome, by 50 years in the biome of temperate forest, and by 100 years in the biome of boreal forest. In consequence, a transformation from tropical forest to artificial land leads to a relaxation time of 62 years and an imputable mean stay of carbon in air of 31 + 25 years.

The relaxation times for forests in Table 2 appear to be reasonable in comparison to the gererally accepted 60–100 years for spontaneous regrowth of temperate forests and 100–200 years for boreal forests. Plausible are also the relatively long relaxation times for (natural) grasslands in Table 2: These can be explained by the slowness of organic carbon formation in soil. Although grass will grow within a few years if a cropland in natural grassland biomes is abandoned, the re-accumulation of carbon in soil below the grass cover requires much more time.

3 Results

Here, per hectare quantities of carbon to air as well as duration factors are given for the most important types of land transformation and land occupation within each of the most relevant biomes of the globe so that the climatic impacts per hectare can be determined in equivalents of fossil combustion carbon. The transparent method allows for the calculation of other and more complex types of land use. In particular, land use types with beneficial climatic impact could also be

Table 3 Biome of tropical forests: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation (see also Tables 8 and 9 for distinction of wet/dry tropical forests)

Type of land use (biome of tropical forests)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation forest to cropland	150.75	31/157=0.20	30.2
Occupation as cropland 1 year	150.75	1/157=0.0064	0.96
Transformation forest to pastureland	120	32.5/157=0.21	25.2
Occupation as pastureland 1 year	120	1/157=0.0064	0.77
Transformation forest to artificial land	150.75	56/157=0.36	54.3
Occupation as artificial land 1 year	150.75	1/157=0.0064	0.96

Table 4 Biome of temperate forests: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation

Type of land use (biome of temperate forests)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation forest to cropland	135	37/157=0.24	32.4
Occupation as cropland 1 year	135	1/157=0.0064	0.86
Transformation forest to pastureland	100	37/157=0.24	24
Occupation as pastureland 1 year	100	1/157=0.0064	0.64
Transformation forest to artificial land	135	87/157=0.55	74.3
Occupation as artificial land 1 year	135	1/157=0.0064	0.86

included, for instance the creation and maintenance of irrigated forest plantations in a region that is too dry for natural growth of forests. In such cases, carbon transfer from air to vegetation/soil precedes the carbon backflow to the air so that the atmosphere is not temporarily charged by carbon but rather temporarily relieved from carbon.

Tables 3, 4, 5, 6, 7, 8, and 9 give the results which can be directly used in LCA applications: If an LCA inventory happens to contain a forest-to-cropland transformation of 1 ha at a location inside of the tropical forest biome, Table 3 indicates a transfer to air of 150.75 t C, taken from Table 2. The imputable mean time of carbon stay in air (also taken from Table 2) is 31 years, which results in a duration factor of 31/157=0.20, or 20% of the mean stay in air of carbon from fossil fuel combustion (157 years). Thus, in view of weighting the climatic impact, the 150.75 t C have to be multiplied by the df 0.20, resulting in only 30.2 ton of fossil-combustion-equivalent carbon (Ceq). In other words, the climatic impact of 1 ha of land transformation from tropical forest to cropland is equal to the climatic impact of the emission to air of only 30.2 t C from fossil fuel combustion. If the transformed land is afterwards occupied as cropland during 1 year, the time to stay in air of the carbon released from vegetation and soil will be increased by one further year, which results in a df of 1/157=0.0064. This means that the climatic impact of 1 ha of land occupation as cropland, at a location inside of the tropical forest biome, is the same as if 0.96 t C is emitted by fossil fuel combustion (the df in all tables are based on a cutoff after 500 years of the Bern carbon cycle model; if a reader contrary to our advice prefers to work with a cutoff after 100 years, the df would have to be increased by a factor 157/47.5=3.3, with a corresponding increase of the Ceq amounts).

As mentioned before, the results for land occupation in Tables 3, 4, 5, 6, 7, 8, and 9 are based on the assumption that the management method in itself, applied during the occupation time, is carbon-neutral so that the area's carbon content would be constant if any aftereffects of the preceding land transformation are separated. In reality, cropping management may increase soil carbon by application of organic fertilizer or decrease soil carbon by intensive deep tillage; the corresponding effect is estimated to be of the order of 0.1–1 t C per hectare and year of occupation (IPCC 2000, Section 4.4.1). These amounts are small in comparison to the ton of carbon per hectare and per year of occupation transferred to air by the precedent transformation, as shown in Tables 3, 4, 5, 6, 7, 8, and 9; a simple addition or subtraction of such effect from occupation management would not change substantially the results. But the adequate way to treat a carbon gain or loss attributable to the occupation management method in itself would require an answer to the type of question: During how many successive years will the carbon content in air be reduced due to the manure-based increase of soil carbon executed during the

Table 5 Biome of boreal forests: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation

Type of land use (biome of boreal forests)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation forest to cropland	150	119/157=0.76	114
Occupation as cropland 1 year	150	1/157=0.0064	0.96
Transformation forest to pastureland	64	67/157=0.43	27.5
Occupation as pastureland 1 year	64	1/157=0.0064	0.41
Transformation forest to artificial land	150	219/157, limited to 1	150
Occupation as artificial land 1 year	150	1/157=0.0064	0.96

Note that duration factor is limited to 1.0 in second to the last row

Table 6 Biome of tropical grassland: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation

Type of land use (biome of tropical grassland)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation grassland to cropland	58	48/157=0.31	18.0
Occupation as cropland 1 year	58	1/157=0.0064	0.37
Transformation grassland to pastureland	0		0
Occupation as pastureland 1 year	0		0
Transformation grassland to artificial land	58	73/157=0.46	26.7
Occupation as artificial land 1 year	58	1/157=0.0064	0.37

period of occupation? As the available knowledge did not enable us to answer this type of question, we have not included the influence of non-carbon-neutral occupation management into Tables 3, 4, 5, 6, 7, 8, and 9.

The amounts we give in Tables 3, 4, 5, 6, 7, 8, and 9 are coarse estimates of mean values. It would have been desirable to give also confidence limits so that the user gets to know the interval within which the true values may be expected with high probability. In the authors' opinion, the quality and the comparability of currently available data do not permit the execution of statistical calculations that lead to reliable confidence limits: In advance of any statistical calculations, the data sets should be cleaned from heterogeneous elements that would distort the results. But currently, this cleaning is difficult to accomplish because data sources are often imprecise in describing their data. Examples: Does the amount of carbon in soil refer to depth 1 m or depth 0.3 m? Does the amount of carbon in biomass exclude or include roots? Where is the spatial delimitation between temperate and tropical forests?

4 Discussion

An inspection of Tables 3, 4, 5, 6, 7, 8, and 9 gives rise to the following comments:

Land occupation as cropland during 1 year shows small Ceq (fossil combustion equivalent ton of carbon) per hectare. This is essentially caused by the fact that 1 ton of carbon from fossil combustion remains in air during 157 years, while land occupation during 1 year leads to a prolongation of imputable carbon stay in air by only 1 year. Comparing now cropland occupation across different biomes, the results confirm that the climatic impact is high if 1 ha of cropland is maintained at a location where forest would be the PNV, while the climatic impact is considerably lower if grassland would be the PNV. This is attributable to the lower carbon transfer per hectare of the transformations to cropland if they are executed inside of grassland biomes.

A land transformation causes a Ceq per hectare that is 30–150 times as high as the corresponding land occupation during 1 year. Nevertheless, the worldwide climatic impact of all current croplands is serious due to the total cropland area of 1600 million of hectares (IPCC 2001, Chapter 3.2.2). Continuing this worldwide cropland occupation for one additional year is therefore a major cause of the current climate problem. We repeat here that the climatic effects of crop consumption are not part of our model. If global croplands were largely used for energy crops and if these energy corps caused a net reduction of fossil fuel use, biofuel studies could come to different conclusions.

Land transformations cause an especially high climatic impact per hectare if boreal forests are transformed to cropland or artificial land. This is mainly due to the fact that

Table 7 Biome of temperate grassland: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation

Type of land use (biome of temperate grassland)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation grassland to cropland	66	55/157=0.35	23.1
Occupation as cropland 1 year	66	1/157=0.0064	0.42
Transformation grassland to pastureland	0		0
Occupation as pastureland 1 year	0		0
Transformation grassland to artificial land	66	105/157=0.67	44.2
Occupation as artificial land 1 year	66	1/157=0.0064	0.42

Table 8 Biome of wet tropical forests: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation

Type of land use (biome of wet tropical forests)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation forest to cropland	231	31/157=0.20	46.2
Occupation as cropland 1 year	231	1/157=0.0064	1.48
Transformation forest to pastureland	186	32.5/157=0.21	39.1
Occupation as pastureland 1 year	186	1/157=0.0064	1.19
Transformation forest to artificial land	231	56/157=0.36	83.2
Occupation as artificial land 1 year	231	1/157=0.0064	1.48

Carbon quantities from WBGU (1998:24). Duration factor same as in Table 4 because data for differentiation wet/dry tropical forests unavailable

the low temperatures slow down the regeneration of plants and soil in the boreal forest biome so that the carbon stay in air after a land transformation is comparatively long. In contrast, transformation from tropical forests to cropland or artificial land causes a lower climatic impact, in spite of the high carbon transfer per hectare, because regrowth of forest in warm and humid climate is a comparatively fast process (however, destruction of tropical forests may cause a drastic reduction of biodiversity, which is not the theme of this study).

The findings of this section illustrate the advantage of the proposed assessment methodology which is not only based on the quantities of carbon transmitted between air and vegetation/soil, but takes into account also the mean time to stay in air of these carbon quantities: Short carbon stay in air means lower climatic impact. Furthermore, our concept compares the actual carbon content of land with the carbon content of PNV so that occupation as urban land or cropland inside a forest biome comes out to be more damaging in comparison to a location in grassland biomes. This is in line with the current methodology for determining biodiversity impacts of land use, and it could be a step ahead for future biofuel studies.

5 Conclusions and recommendations

Tables 3, 4, 5, 6, 7, 8, and 9 assist the LCA practitioner in determining the climatic impact from main types of land use inside of the main biomes of the globe. Additional types of land use could be calculated on the basis of the concept presented in the study and the cited data sources. Data availability will cause higher problems if land use inside of biomes other than those treated in Tables 3, 4, 5, 6, 7, 8, and 9 should be assessed.

In spite of the excellent work of IPCC, the quality of available data on carbon content in vegetation and soil, on carbon transfers to air due to particular land use types, and on the duration of stay in air of the carbon is still limited and needs improvement. Providers of empirical data should be more explicit on the boundary conditions of their data so that the comparability of different data sets can be checked prior to statistical uncertainty calculations. Furthermore, data on important non-CO_2 greenhouse gas transfers due to land use should be available to the same extent as for CO_2.

Nevertheless, a coarse LCA assessment of the climatic of land use is practicable whenever the LCA inventory contains the necessary information. Together with the

Table 9 Biome of dry tropical forests: carbon transferred to air, df, and fossil-combustion-equivalent carbon transferred to air for most important types of land transformation and occupation

Type of land use (biome of dry tropical forests)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation forest to cropland	66.5	31/157=0.20	13.3
Occupation as cropland 1 year	66.5	1/157=0.0064	0.43
Transformation forest to pastureland	50	32.5/157=0.21	10.5
Occupation as pastureland 1 year	50	1/157=0.0064	0.32
Transformation forest to artificial land	66.5	56/157=0.36	23.9
Occupation as artificial land 1 year	66.5	1/157=0.0064	0.43

Carbon quantities from WBGU (1998:24). Duration factor same as in Table 4 because data for differentiation wet/dry tropical forests unavailable

planned separate studies covering the land use impacts on biodiversity and on biotic production, a fairly complete treatment of land use worldwide will be possible.

References

Alean J (2009) Morteratsch vegetation. Succession of vegetation in the glacier forefield. http://www.swisseduc.ch/glaciers/morteratsch/vegetation/index-en.html

Ceschi I (2006) Il bosco del cantone Ticino. Dipartimento del Territorio Cantone Ticino, Bellinzona CH

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319:1235–1238

Frenzen P (2009) Mount St. Helens cfnv National Volcanic Monument, Vegetation Around the Volcano "Before and After the 1980 Eruption". http://www.fs.fed.us/gpnf/mshnvm/digital-gallery/25yearsofrecoverybeforeandafter.htm

IPCC (2000) Land use, land-use change and forestry. IPCC Special Report, Cambridge University Press, Cambridge. http://www.grida.no/climate/ipcc/land_use/157.htm

IPCC (2001) Climate Change 2001, Working Group 1: The Scientific Basis, chapter 3, Carbon cycle. http://www.grida.no/climate/ipcc_tar/wg1/095.htm

IPCC (2007) IPCC Fourth Assessment Report, Working Group 1, Report "The Physical Science Basis. http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Milà i Canals L, Bauer C, Depestele J, Dubreuil A, Freiermuth Knuchel R, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007) Key elements in a framework for land use impact assessment within LCA. Int J Life Cycle Assess 12 (1):5–15

Reijnders L, Huijbregts M (2008) Biogenic greenhouse gas emissions linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans. J Clean Prod 16:1943–1948

Searchinger T, Heimlich R, Houghton R, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. Science 319:1238–1240

WBGU (1998) Die Anrechnung biologischer Quellen und Senken im Kyoto-Protokoll, Sondergutachten 1998. http://www.wbgu.de/wbgu_sn1998.pdf

Wild World (2009) Terrestrial ecoregions of the world. http://www.nationalgeographic.com/wildworld/terrestrial.html

Zah R, Boeni H, Gauch M, Hischier R, Lehmann M, Waeger P (2007) Life cycle assessment of energy productions—environmental assessment of energy productions. Executive Summary. http://www.bfe.admin.ch/dokumentation/energieforschung/index.html?lang=de&publication=9146